RE-223

RESEARCH IN GAS-SURFACE INTERACTION 1964-65

Part II

A Shock Tube Driven Molecular Beam for Gas-Surface Interaction Experiments

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RESEARCH DEPARTMENT

GRUMMAN AIRCRAFT ENGINEERING CORPORATION

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PART II

A Shock Tube Driven Molecular Beam for Gas-Surface Interaction Experiments

by

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FOREWORD

This report, in three separate parts, summarizes the research conducted over the past year on the interaction of gas molecules and solid surfaces under NASA Contract NASw-1027. Previous work in this field (under NASr-104 and NASw-709) was reported in Refs. 1 through 4, and the work described herein relies heavily on the earlier results. We expect to continue this research along the lines suggested in the following discussion.

Part I of this report describes the additions and modifications that have been made to our computer program for calculating molecule-surface interactions, gives results which represent the early findings from these modifications, discusses parametric correlation work that has resulted in a much improved understanding of the results of some of our previous calculations, and presents the plans we have for further application of all of these approaches. Part II describes our molecular beam apparatus in its present form and gives a summary of our research on the generation of high intensity molecular beams. Remaining problems and plans for experiments which are now getting under way are also described. Part III is a progress report on the experimental development of methods for the preparation of atomically controlled surfaces to be used for testing in the molecular beam. The high vacuum apparatus for those experiments was described in a previous report (Ref. 4). (Part I, Part II, and Part III are identified as RE-222, RE-223, and RE-224, respectively.)

ACKNOWLEDGMENTS

The authors would like to express their appreciation of the help of many people. Frank Schaeffer, the technician who has worked with us on the apparatus, was invaluable to our efforts. Wayne Konopka of the Grumman Instrumentation Department and Gerard Connell of the Grumman Research Department rendered invaluable services in the design, acquisition, and application of many different instrumentation systems. We are also grateful for the support and encouragement of our colleagues in the Grumman Research Department, and of Mr. Alfred P. Gessow and his staff in the Fluid Physics Branch, Research Division of the NASA Office of Advanced Research and Technology.

ABSTRACT

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The application of pulsed molecular beams to gas-surface interaction experiments is discussed, making use of the results of experimental investigation of four basic configurations. The configuration closest to that recommended by Skinner and Moyzis is found to be most promising, primarily because of its elimination of low energy gas entrainment by the hot beam and its high skimmer transmission at skimmer intensities of the order of 10^{20} molecules/ cm^2-sec. Low energy gas density was measured directly in other configurations with ionization gauges both on the beam axis and at large off-axis displacements, and the measured density was found in some cases to be greater than that of the high-energy portion of the flow. This low energy gas would make gas-surface experiments impossible. The use of a two-stage skimmer appears to remove these difficulties. Beam divergence angle, intensity, and energy are quite acceptable, and can be predicted with acceptable accuracy by simple calculation methods and scaling laws. Some evidence of unsteadiness during the test interval has been found with the two-stage nozzle, two-stage skimmer configuration, but this is felt to be only a mechanical noise problem in the instrumentation system.

author

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INTRODUCTION

The recent literature provides three extensive surveys of techniques and potential applications of high intensity molecular beams (Refs. 5-7). In this report we will restrict ourselves to those points which bear directly on the problems of using a shock tube source beam to simulate epithermal (0.1 - 10 ev per particle) energy molecular flows for gas-surface interaction research. The work of Skinner and his co-workers (Refs. 8 and 9) is particularly pertinent to this discussion, for the problems of impulse facilities will be seen to be quite different from those of steady-state molecular beams, and theirs are the only published data in the field at this writing.

There are three basic arguments favoring the use of shock tubes (or similar single-pulse sources) for molecular beams. These are the higher source energies available (without problems of vaporizing, melting, or weakening materials in the apparatus), the ease of achieving and maintaining very low background gas densities throughout the test interval, and the possibilities of performing true controlled-surface experiments by precleaning the surface and conducting the experiment before significant contamination can take place. The primary arguments against single-pulse techniques are the difficulties of making measurements in nonrepetitive millisecond time intervals, and the impossibility of scanning during operation to detect continuous distributions or to optimize performance of the apparatus. The single pulse form has some of the advantages of modulated beam techniques, but cannot employ phase sensitive detection.

Most of our work thus far has been exploratory. We have been primarily concerned with determining the characteristics of the different types of configurations available, rather than on careful calibration of the instrumentation. We are now entering the phase in which experiments on surface interaction will be attempted, and the process of optimization and more accurate calibration of detectors is now under way. The signal levels, velocities, and intensities quoted in this report, however, should be understood to be nominal values, often inferred from heat transfer gauge measurements that have an inherent accuracy of about 15 per cent. Added to this uncertainty is the fact that neither the gauge accommodation coefficient, nor the states of internal degrees of freedom in the gas is known. In spite of these difficulties, the consistency and reproducibility of the measurements taken as a whole have been sufficient for us to feel quite confident in our conclusions as to good and bad ways of running a molecular beam, particularly since they generally agree with those of Skinner and Moyzis (Ref. 9).

An over-all description of the molecular beam apparatus has been included in the Appendix, and details of the various elements are discussed in the text. Figure 1 shows a schematic diagram of the apparatus, and Fig. 2 is a photograph of the actual installation. Figure 3 shows the configurations we have used in the work to date.

GENERATION OF THE MOLECULAR FLOW

The need for an adequate signal at the final detection stage dictates that a single-pulse molecular beam operate near the maximum possible intensity. Exploitation of the Kantrowitz-Grey concept of a nozzle source (Ref. 10) is the first step in this direction. In addition, the removal of the requirement to pump away the entire nozzle mass flow grants us the opportunity to work at source densities that are an order of magnitude higher than those in use with steady-state beams. Source pressures in current use in our apparatus range from 1 to 100 atmospheres. This situation has the advantage that high collision frequencies prevail until quite high Mach numbers are reached, and a very high percentage of the total energy of the source gas is converted to translational kinetic energy. Freezing of translational and internal degrees of freedom in rapid expansions is under intensive study by many investigators (c.f. Brook and Oman, Ref. 11, Brook, Ref. 12, and Knuth, Ref. 13), and consistently shows lower final temperatures at increased stagnation density.

We use a family of 12.5° half-angle, conical converging-diverging nozzles. Throat sizes available are 0.159, 0.238, 0.317, and 0.635 cm. The nozzles are machined into interchangeable stainless steel balls that are rotated by a precisely timed pneumatic actuator. The nozzle acts as a valve at the end of the shock tube, preventing static gas from leaking into the test chamber until just before the shot, and then closing to prevent both loss of vacuum and entry of diaphragm fragments after the shot. The nozzle swings into aligned position, dwells for 2-3 milliseconds, and returns to a closed position in an over-all time of about 6 milliseconds. Although nozzle timing relative to the shock tube period still causes about 20 per cent of our runs to fail, the system works well enough for present purposes.

The flow field generated by the nozzle has been probed extensively with thin-film heat transfer gauges mounted on the flat ends of cylindrical rods. The flow was found to be hypersonic and obeyed a $1/r^2$ decay of ρu^3 along the centerline (within the limits of measurement error) and the uncertainties in Cheng's theory for blunt body heat transfer (Ref. 10). This is consistent with rough measurements of stream velocity by time of flight that indicate a constant u of 85 to 95 per cent of the thermodynamic limit (depending on shock tube conditions) and a conical flow field which would produce $\rho \sim 1/r^2$. Measurements taken in a position off of the centerline showed no anomalies.

Among the phenomena observed in continuous and modulated nozzle beams is the infiltration of the nozzle flow by background gas (c.f. Ref. 15), and the formation of a Mach disc or recompression zone at far downstream stations. Neither of these phenomena are to be expected in single-pulse beams because the background pressures (10^{-5} torr) are much lower; and although we have not made a complete survey of the far-field flow, we do not see any evidence of recompression in our data. Because we use a converging-diverging nozzle, the exit plane Mach numbers are sufficiently high that the leading characteristics from the edges of the nozzle are divergent.

SKIMMING AND COLLIMATION

Most of the difficult problems associated with formation of a high intensity beam center about the skimmer, the inlet that separates a single ray of molecules from the nozzle flow field. The most important requirement of a good skimming configuration is that it cause a minimum of energy loss and angular deflection in the transmitted molecules. It is highly desirable that the attenuation of the incident mass flux be as small as possible, a criterion that is strongly related to the energy decrement, but is not necessarily the same. Other important requirements are to keep the final beam diameter fairly small and to prevent low energy molecules from entering the test region if one is performing surface scattering experiments. The beam diameter limits the angular resolution of measurements of the scattered flux distribution and the slow molecules show up as false signals. Axisymmetric designs are preferable to slits, because measurements of lateral scattering are important in surface interactions.

There are two quite different ways to operate a skimmer successfully. The first is at very high incident intensity, where molecules reflected from the walls are confined by collision mechanisms to a thin boundary region near the walls. This configuration can be viewed as a two-stage nozzle in which the skimmer is the second stage (c.f. Configurations III and IV in Fig. 3). The skimmer acts as a source for the subsequent flow field which scales quite well as a conical jet. The local intensity is proportional to upstream intensity and skimmer inlet area, and has a typical radial distribution similar to that shown in Fig. 4. We found no effect of skimmer shape when the external angle was small enough to allow an attached shock, and internal half-angle was at least 12.5°.

The second successful method of skimmer operation is to keep the incident intensity sufficiently low to make the probability of collision of an incident molecule with a member of the cloud of molecules reflected from the skimmer walls acceptably small. The first method is undesirable when used alone, because it usually results in too great a beam divergence angle. At the relatively high beam intensities (we would like to use 10^{18} molecules/cm^2-sec and above) there are a multitude of complicating factors which also cause difficulties with the second method. Intensities between completely continuum and about 10^{20} molecules/cm^2-sec usually result in a very high degree of blockage of the skimmer.

Skimming at Low Intensity

A series of calculations of the undeflected fraction in the limit of low incident intensity and infinite speed ratio was made by Oman (Ref. 16) using a simplified model of the flow field and a generalized skimmer geometry. A correlation of the results of these calculations indicates that the fraction transmitted is inversely proportional to the incident intensity and skimmer lip thickness, and only very weakly dependent on inlet radius. The external cone angle was found to have a very strong effect, namely that increased cone angles decreased the fraction transmitted as an exponential factor. The scattering processes downstream of the skimmer inlet were shown to be very important, and to depend strongly on the amount of scattering that occur upstream. Upstream scattering is the source of the slow molecules carried into the skimmer, and an increase in their density increases the importance of the confining effect of the internal skimmer walls. Recent experimental data presented by Skinner and Moyzis (Ref. 9) show the importance of this effect on skimmer transmission quite dramatically.

Because of the approximate nature of the above calculations and the labor involved in the required experimental calibrations, we have not carried out a complete experimental check of the theoretical correlation of Ref. 16. We have found however that identical runs on otherwise identical skimmers resulted in a total energy transmission directly proportional to skimmer inlet area at an incident intensity such that the estimated fraction of the free-stream flux transmitted was about 0.2 in both cases. This appears to confirm the most surprising result of Ref. 16, namely, that attenuation is nearly independent of inlet radius. We have also determined that the theory appears to underestimate the effects of collisions inside the skimmer. An internal divergence half-angle of 12.5°, which was chosen by the theory to give negligible internal losses, showed much larger losses in this regime than those of a similar skimmer having a 30° internal half-angle. Both of these skimmers had a basic 45° external half-angle, but the former had a 22.5° angle at the tip, opening to 45° along a circular arc profile (see Fig. 5), while the latter was conical.

External Scattering

We have no data for the effects of external cone angles on skimmer performance. Bier and Hagena (Ref. 13) present extensive results on optimization of skimmers and other beam elements. Some of their conclusions are influenced by back pressure effects and condensation, neither of which should appear in the case of a shock tube source. Therefore, their recommendations should be accepted with some reservations, although these considerations are quite relevant to steady, low energy beams.

Of first order importance is the effect of the diameter of the jet incident on the skimmer. Skinner and Moyzis (Ref. 9) report data on the attenuation of the beam energy flux as a function of position downstream of the skimmer. When the jet hitting the skimmer is large, they find the beam attenuates much more rapidly than $1/r^2$ from the nozzle. When the jet is preskimmed by a larger stripper cone, they find that skimmer losses virtually disappear and the energy flux does decay as $1/r^2$ from the second stage of their nozzle. This behavior is attributed to "cold" gas which has been generated by collisions and which flows along with the "hot" beam in the unstripped case. The stripper cone is arranged so that it greatly reduces the flux on the skimmer walls near the inlet without materially affecting the core flow.

Although we have not been able to detect the sharp attenuation rate Skinner and Moyzis displayed, we have found striking confirmation of their mechanism in a somewhat different way. Using a single stage nozzle (Configuration I in Fig. 3) and a large nozzle-skimmer distance (465 throat diameters) we find a very large attenuation across the skimmer (incident flux $\approx 10^{20}$ N_2 molecules/cm^2-sec, $u \approx 2.2 \times 10^5$ cm/sec, skimmer inlet diameter 0.30 cm, fraction transmitted at original direction and energy $\approx 3 \times 10^{-3}$). The transmitted beam, which is still detectable with thin-film heat transfer gauges, shows a spreading angle of less than 1/2°; the beam decays as $1/r^2$ from the nozzle, and has a time of arrival which indicates no detectable loss in velocity. In attempting to employ this beam in crude reflection experiments (see <u>Surface Scattering Experiments</u>), we found that ionization gauges as much as 50° off the beam axis detected signals of the order of one-tenth of the magnitude of an identical gauge on the centerline (see Fig. 7a). Furthermore, the majority of the off-axis signal arrived much later than the hot gas signals given by the heat transfer gauges.

Because the ionization gauge detects instantaneous density, these measurements indicate that cold gas was effusing into the chamber at a rate many times the beam flow rate. This cold gas, generated during the test period by the skimming process, has random velocity vectors, and therefore fills the entire chamber. The post-skimmer attenuation found by Skinner and Moyzis(Ref. 9) undoubtedly occurs in our case also, but the attenuation is substantially completed before reaching our first measuring station, because the cold-gas collision frequency drops off rapidly with distance. The beam we detected was apparently composed of those few molecules that escaped collisions entirely, and therefore displayed the structure of the nozzle source as if the skimmer were not there.

As a further confirmation, we installed the stripper cone shown in Fig. 6 ahead of the skimmer (Configuration II in Fig. 3). The off-axis cold gas signals were reduced by a factor of about 50, while the hot beam intensity and the fraction of the energy flux transmitted increased greatly. Unfortunately there is no reliable quantitative measure of this increase. The time of arrival from the ionization gauge now coincided with that indicated by a heat transfer gauge, and the initial rate of signal rise indicates a high Mach number (see Fig. 7b). An increase in the duration and quality of the centerline pulse is also apparent.

It is important to realize that the above experiments were performed under conditions that produce very high attenuation at the skimmer. Use of a two-stage nozzle greatly reduces the intensity at the skimmer and thereby increases the fraction transmitted. We have taken a large amount of heat transfer data with this configuration, but without stripper cones installed, and without using ionization gauges to measure the amount of cold gas carried with the beam. We are now using the two-stage nozzle to vary the incident intensity on the stripper-skimmer combination (Configuration IV in Fig. 3) in order to determine the best operating range for use in surface experiments. Ionization gauge data show a large reduction in cold gas density as well as an increase in both quality and duration of the centerline pulse (see Fig. 7c). The presence of a cold gas flow is extremely detrimental to surface experiments, because the detectors cannot distinguish between cold gas and the reflected distribution. An example of the beam produced by the two-stage nozzle and a conventional skimmer (Configuration III, Fig. 3) at a nominal skimmer inlet intensity of 5×10^{18} N_2 molecules/cm^2-sec is shown in Fig. 8. The approximate fraction of energy flux transmitted in this case is 0.2. The only present heat transfer data for Configuration IV are unreliable because of unsteadiness during the test interval, but they strongly indicate a dramatic increase in skimmer transmission over the corresponding case for Configuration III. It is not yet known if any degradation in beam Mach number, divergence angle, or steadiness is inherent with this configuration. No attempt has yet been made to optimize the stripper cone or its location.

Transient Skimmer Phenomena

The two characteristic types of flow patterns associated with the use of skimmers at very high or very low intensities have been described above for steady flow. When the incident flow is impulsively started from a high vacuum initial condition, the establishment of these flow patterns must also be considered. In Ref. 3 we presented a crude analysis which shows the characteristic times associated with the establishment of each type of flow increase as the intensity decreases. Data on these phenomena are inherently very inaccurate, but a rough correlation plot for a single skimmer geometry is shown in Fig. 9. The important point is that unsteadiness consistently develops in the post-skimmer flows if the skimmer intensity is in the intermediate range between very fast establishment times and very long ones. Fortunately, the flow in the two-stage nozzle establishes in extremely short times, and the flow is essentially steady in low-intensity skimming for times much greater than test times whenever the fraction transmitted is useful.

SURFACE SCATTERING EXPERIMENTS

The ultimate goal of a molecular beam experiment on gas-surface interaction is to measure the velocity distribution function and the rotational and vibrational states of the reflected molecules as a function of angle relative to a well characterized surface. From these data any desired statistical property of the re-emitted population can be determined for each incident angle and translational energy. In the present program we hope to be able to determine relative flux distributions and a measure of the distribution of translational velocities at each angular position, but we do not have any present plans to attempt internal state measurements.

Detectors

The basic detection method used is an ionizing detector of the type developed by Hagena and Henkes (Ref. 17). This detector has the advantage that the boundaries of its ionizing region are very well defined, giving it a high spatial and temporal resolution for time-of-flight measurements. Sensitivities appear at this time to be adequate, although increased sensitivity will always permit greater resolution with a given beam signal. The detector can also be adapted for use with a mass spectrometer and/or an electron multiplier. The detector, being of the through-flow type, can be used to monitor the characteristics of the incident beam without significantly affecting its properties (ionization probability is $0\ [10^{-4}]$), and this feature is extremely valuable.

We also employ thin-film heat transfer gauges to measure the energy flux of the incident molecular beam. Because this energy flux quantity is very close to $1/2\ \rho u^3$ in the region we are presently operating, the heat transfer gauge complements the ionization gauge (which measures ρ) very well. In the preliminary tests we are now conducting a heat transfer gauge is used as a target, after passing the incident beam through an upstream ionization gauge. A good run therefore gives us two different pulses with which to work, and from which we can determine mean velocity and velocity spread in the initial part of the flow period, as well as an accurate time of arrival at the target.

Future Experiments

Although our first attempts to measure scattered density distributions were foiled by the cold gas flows described in the Skimming and Collimation Section, we feel that these problems are now well resolved. We now expect to work with Configuration IV of Fig. 3, which still requires some further investigation. The first targets will be heat transfer gauges, as these provide a great deal of additional information about beam quality and performance. We are concurrently conducting a separate detector optimization and calibration experiment using a small effusion source. The next major hurdle is to determine the maximum angular resolution we can achieve. This is determined by the incident beam intensity, the detector sensitivity (or signal/noise limit), and the fraction of the reflected sample we admit into each detector. Present goals are to try for an angular resolution of 0.001 steradian, but this may prove to be too optimistic.

CONCLUSIONS

There appears little doubt at this time that the configuration recommended by Skinner and Moyzis (Ref. 9), namely, a two-stage nozzle followed by a two-stage skimmer, is the best yet devised for high energy, pulsed molecular beams. The low-energy gas entrainment that Skinner and Moyzis inferred from their experiments has been measured directly in the present work, and this low-energy gas essentially disappeared when their concept of a two-stage skimmer was employed. Indirect evidence also indicates a skimmer transmission factor of the order of unity when the stripper is employed, compared with 0.2 for a conventional skimmer. The absence of the cold gas flow is an essential requirement for gas-surface interaction experiments. Because the cold-gas interference will become more important as source energy is increased, it would seem that such a configuration would also be the best for a high energy steady-state beam.

There does not appear to be any further barrier to starting surface interaction experiments. Although the limits of the range of usable operation for the present configuration have not yet been found, energy flux, density, and velocity measurements have thus far failed to indicate any anomalous behavior, except for unsteadiness which we believe is mechanical noise. The beams generated without strippers are well defined (spreading angles $< 1/2°$), show the correct times of flight, and have very small random velocities in both radial and axial directions. There is no reason to expect that the strippers will degrade this performance. Intensities, though only roughly known, can be dramatically high

(> 10^{19} molecules/cm^2-sec at our target location). Perhaps most important are the effects on signals of changes in skimmer and throat areas, source density, and axial position of the detector can be predicted in a simple way.

Explanation of the success of the stripper cone in eliminating cold gas entrainment and in increasing skimmer transmission is still largely based on speculation. It appears, however, that the sharp reduction of cold gas would only result if the cold gas cloud generated by, and carried through, the stripper does not penetrate far enough into the core flow to get into the skimmer. Because the stripper shields a very large portion of the external surface of the skimmer, the cold gas cloud generated by the skimmer itself is strongly reduced. It may also be that the diameter of the jet impinging on the stripper plays an important role. Skinner and Moyzis' analogy to a viscous interaction is certainly useful in describing the qualitative nature of the flow pattern, but the actual process by which the stripper shields the skimmer without interfering with the core flow is a challenging problem in kinetic theory.

APPENDIX

DESCRIPTION OF GRUMMAN MOLECULAR BEAM SYSTEM

A schematic of the Grumman molecular beam system which indicates the basic operation and important features of the system is shown in Fig. 1. The source of high energy gas consists of a 38.1 cm id, 11 meter long shock tube with a small hypersonic nozzle at the reflected shock end. The shock tube is presently being used with a cold helium driver with A, N_2, and air as the driven gases.

The nozzle is cut into a 5.1 cm diameter stainless steel ball that rotates in a socket so as to produce a vacuum valve between the shock tube and the outer vacuum chamber. It has an actuation cycle of about 6 msecs, with a period of 2 msecs during which it is locked in alignment with the centerline of the apparatus. Nozzles can be changed by replacing the ball.

Behind the nozzle in the large vacuum chamber there are two conical skimmers, mounted in tandem, which collimate the nozzle flow into a narrow beam of high-energy molecules. The distance between the nozzle throat and first skimmer may be varied from 38 cm to 7 cm, or the first skimmer and mounting baffle may be removed entirely. Recently, we have added a conical stripper cone just ahead of the second skimmer; the tip of the stripper is 30.48 cm behind the first skimmer tip. The second skimmer is an integral part of the inner or test chamber and is backed by a manually operated ball valve. This valve is used to isolate the test chamber from the expansion chamber until the proper test conditions are attained. Both chambers are evacuated to 10^{-5} mm Hg and then the outer chamber is held by a 4-inch pumping system while the test chamber is evacuated to 10^{-7} mm Hg with a 10-inch pumping system. The pumping system used with this apparatus consists of one 10-inch (PMC 4100) and one 4-inch (PMC 720) oil diffusion pump backed respectively with 310 and 30 cfm mechanical vacuum pumps. Both pumps have liquid-nitrogen-filled baffles.

After collimation the beam passes into the inner or test chamber where it impinges on the target. The reflected molecules are then counted by an array of detectors to yield their spatial density distribution and a measure of their velocity from time of flight measurements. Two types of detectors are in use with this system: thin film heat transfer gauges and electron bombardment detectors. The thin film gauges consist of an array of platinum elements. The variation in resistance of the platinum elements is a function of the heat transfer to the elements and thus yields an output which is directly proportional to the product of beam intensity and molecular energy. The electron bombardment detectors are specially constructed ionization gauges based on a design of Hagena and Henkes (Ref. 17). A beam of electrons is accelerated to 100 ev and allowed to pass perpendicular to the flux of molecules which enters the gauge through a conical skimmer inlet. The positive ions formed are then collected on a probe located downstream of the electron beam. The resulting ion current is directly proportional to the instantaneous local density of the molecules. Static sensitivities of approximately 2×10^4 μa per milliamp per torr have been obtained with this gauge. The electron bombardment detectors also make excellent time of arrival gauges and should be quite adequate for use in time of flight measurements, since the electron beam thickness (approx. 1/2 cm) is small.

The target and detectors are mounted on independent supports that are externally controlled. Both supports have a single degree of rotational freedom. The target support is centrally located between the two detector hoops with the center of the target coincident with the molecular beam. Relative hoop angles and initial detector spatial locations may be preset when the target is mounted by entering the test chamber through a quick access rear door. During an experiment, the target angle of attack may be varied from 0 to 90° and the detector arrays may be varied from 0 to 180° externally. A detector may be placed in the incident beam to measure its density without appreciably affecting it.

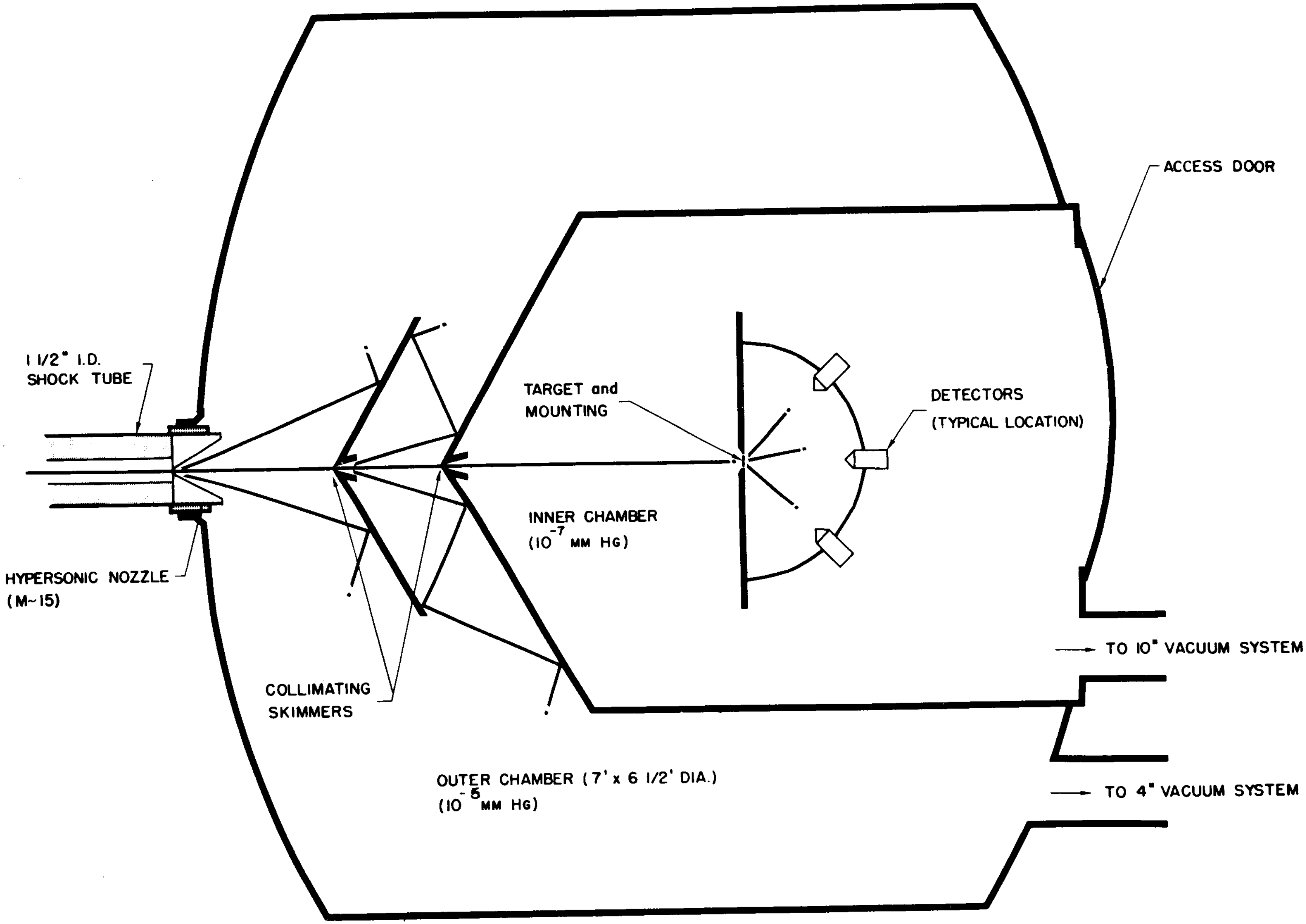


Fig. 1 Schematic Diagram of Molecular Beam Apparatus

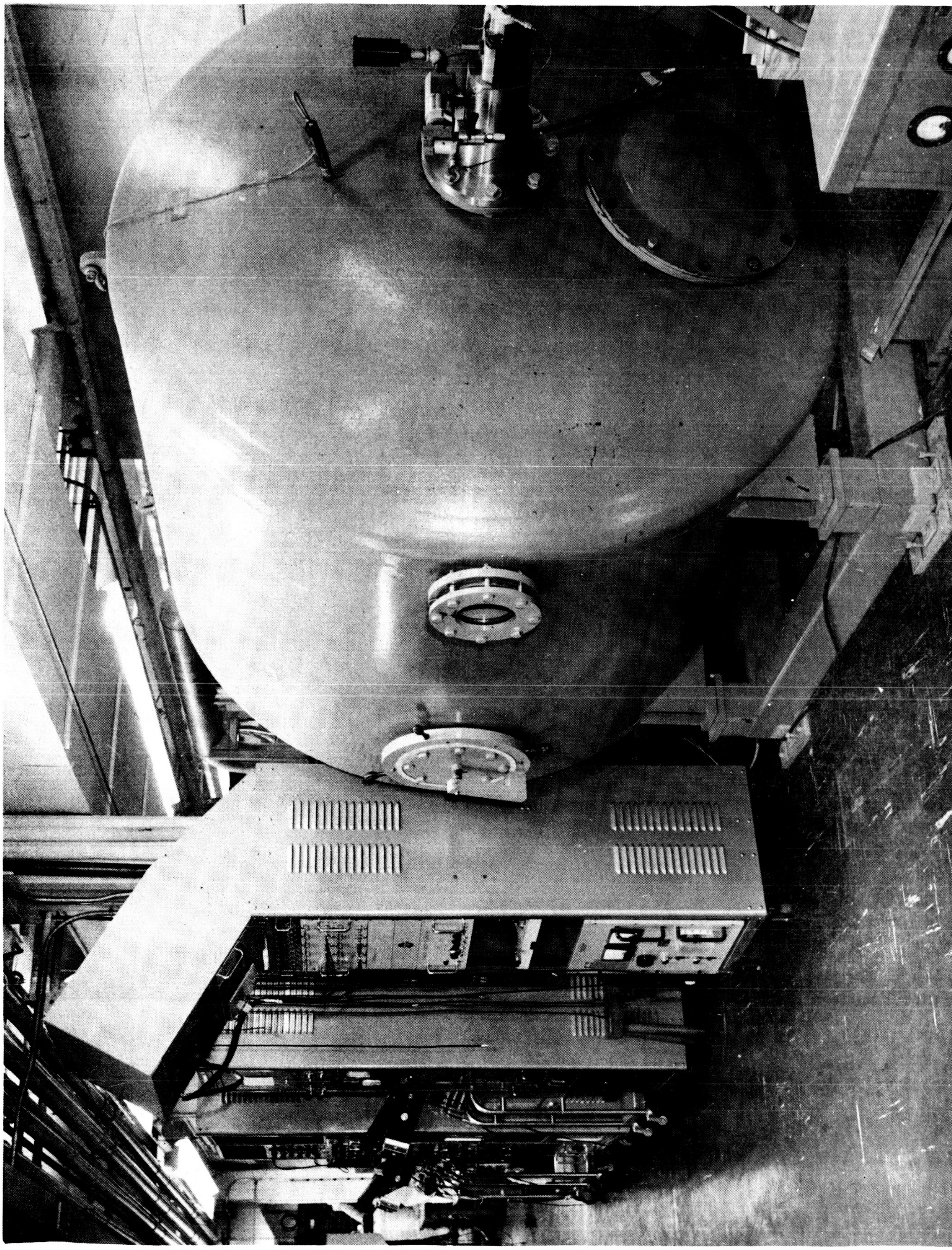


Fig. 2 Photograph of Molecular Beam Apparatus

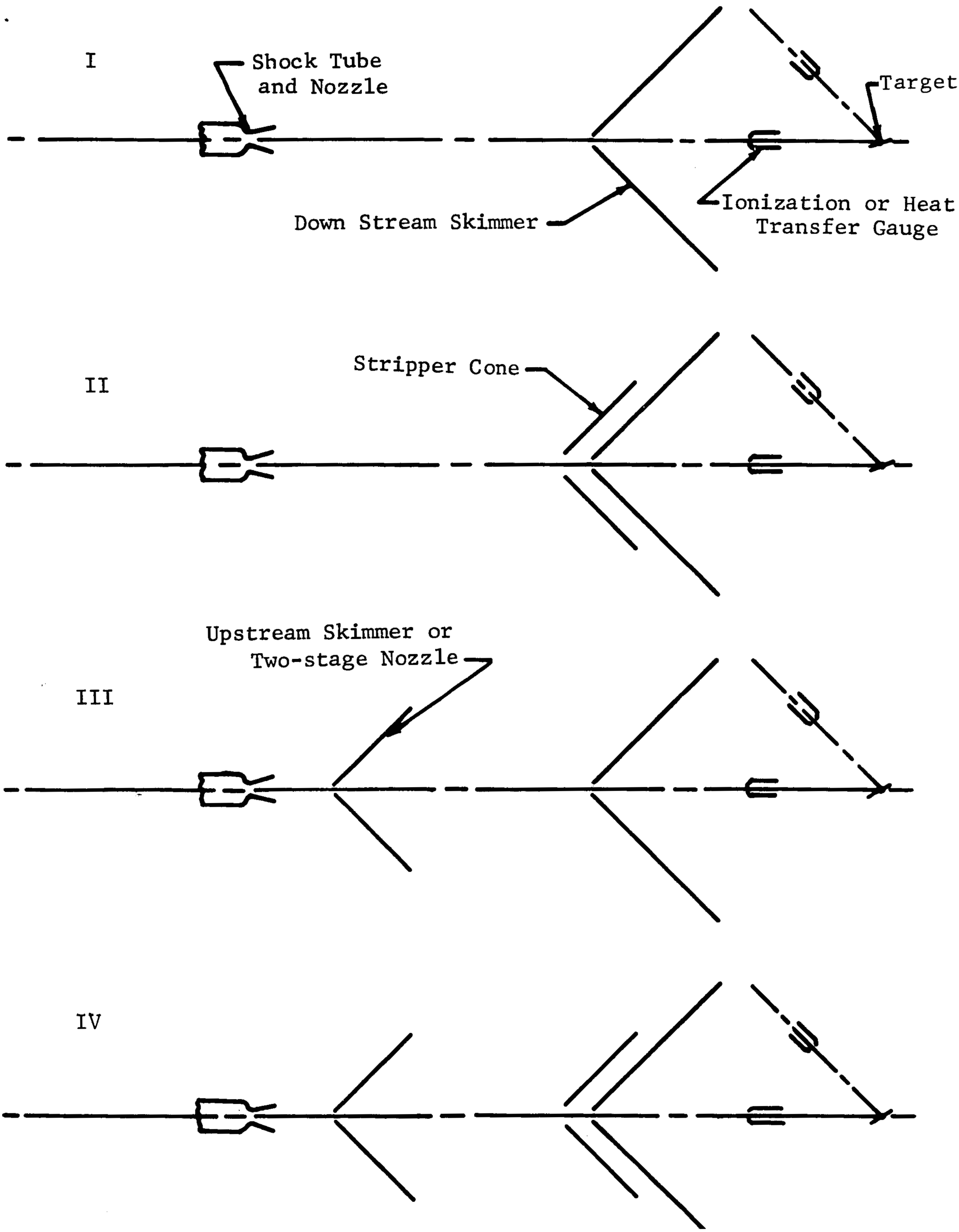
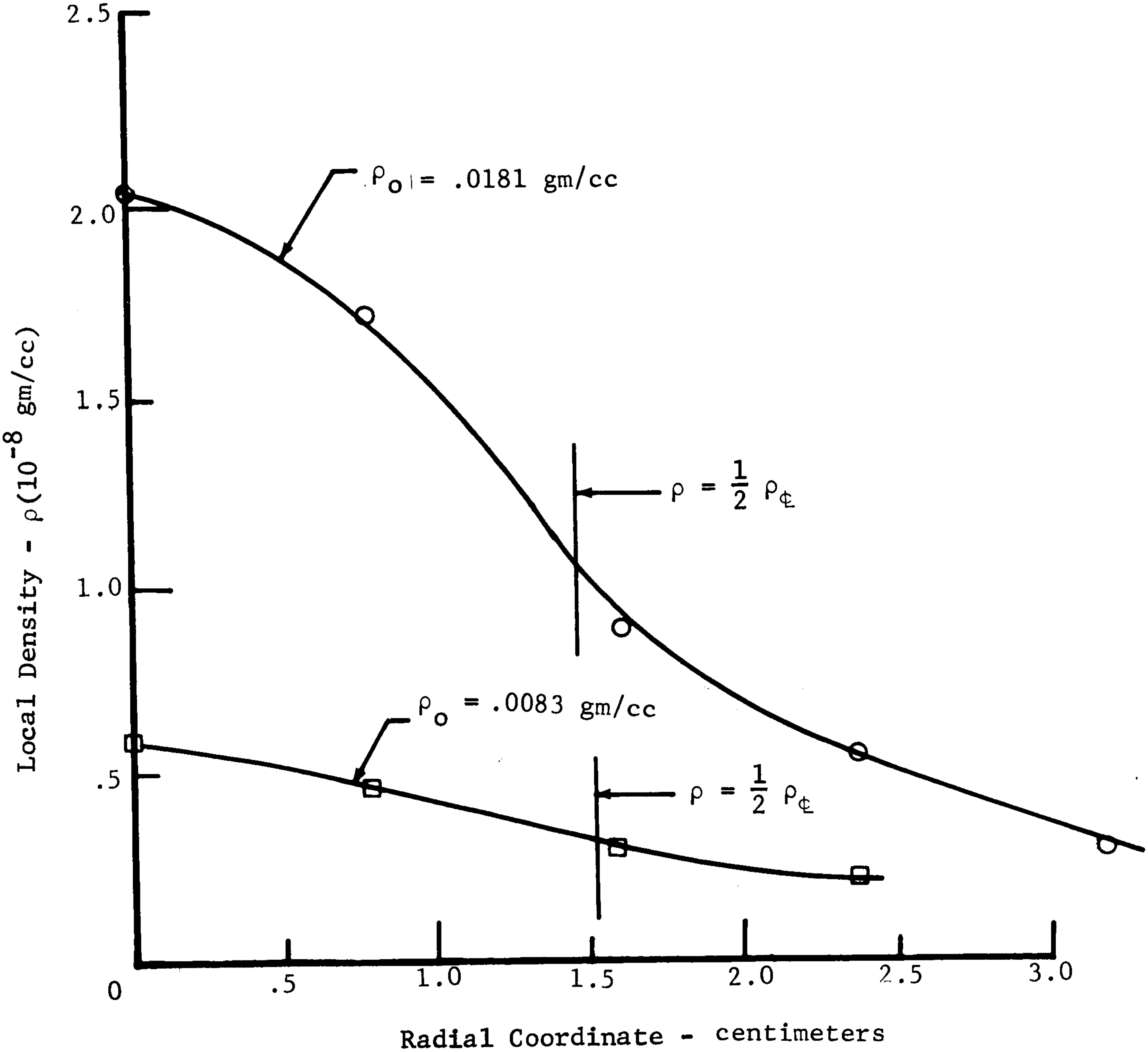


Fig. 3 Molecular Beam Configurations Considered



Throat diameter = .318 cm
Skimmer inlet diameter = .152 cm
Internal half-angle-angle = 12.5°

Fig. 4 Radial Density Distribution 27.31 cm Downstream of First Skimmer Inlet

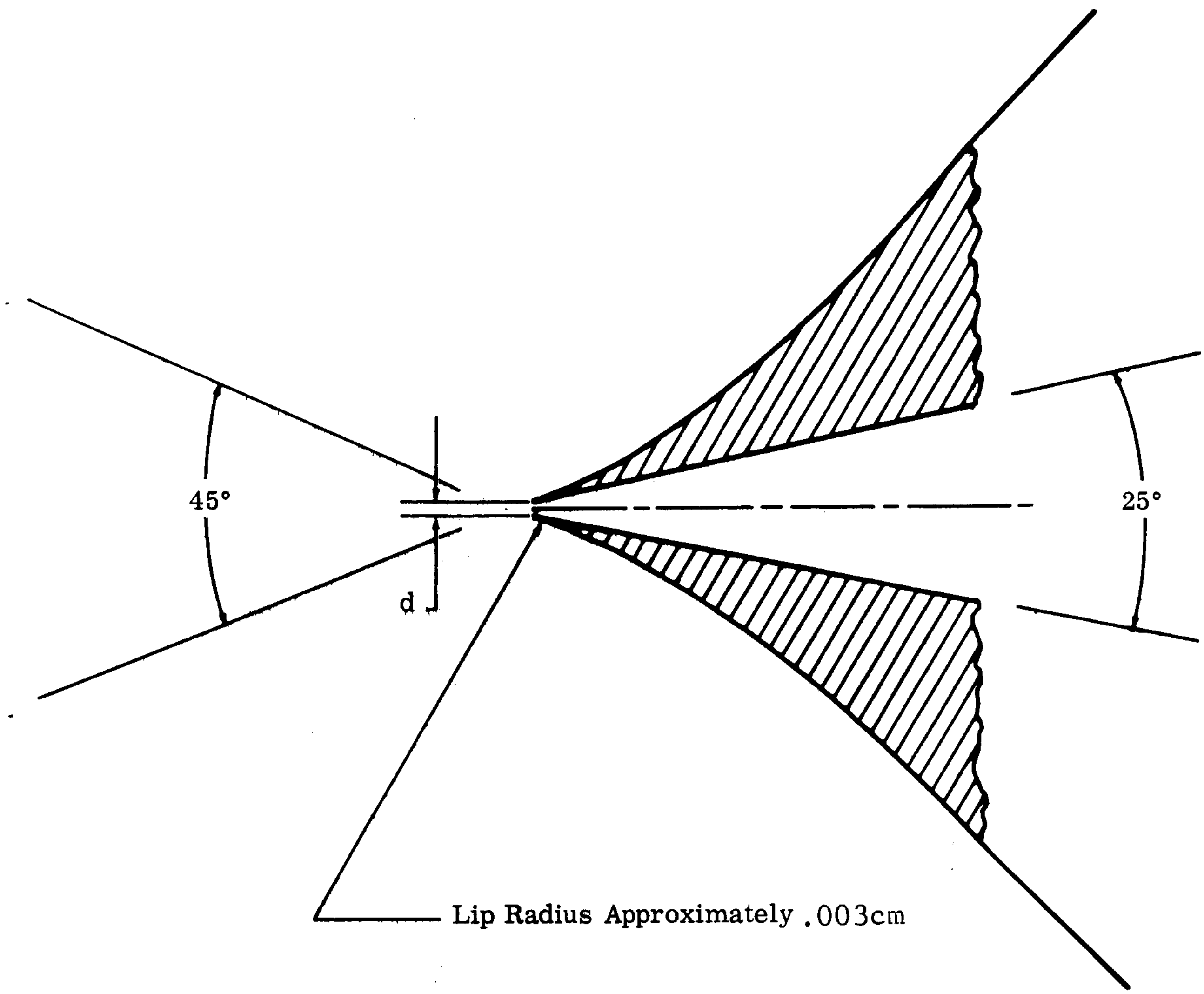


Fig. 5 Present Geometry for First Skimmer

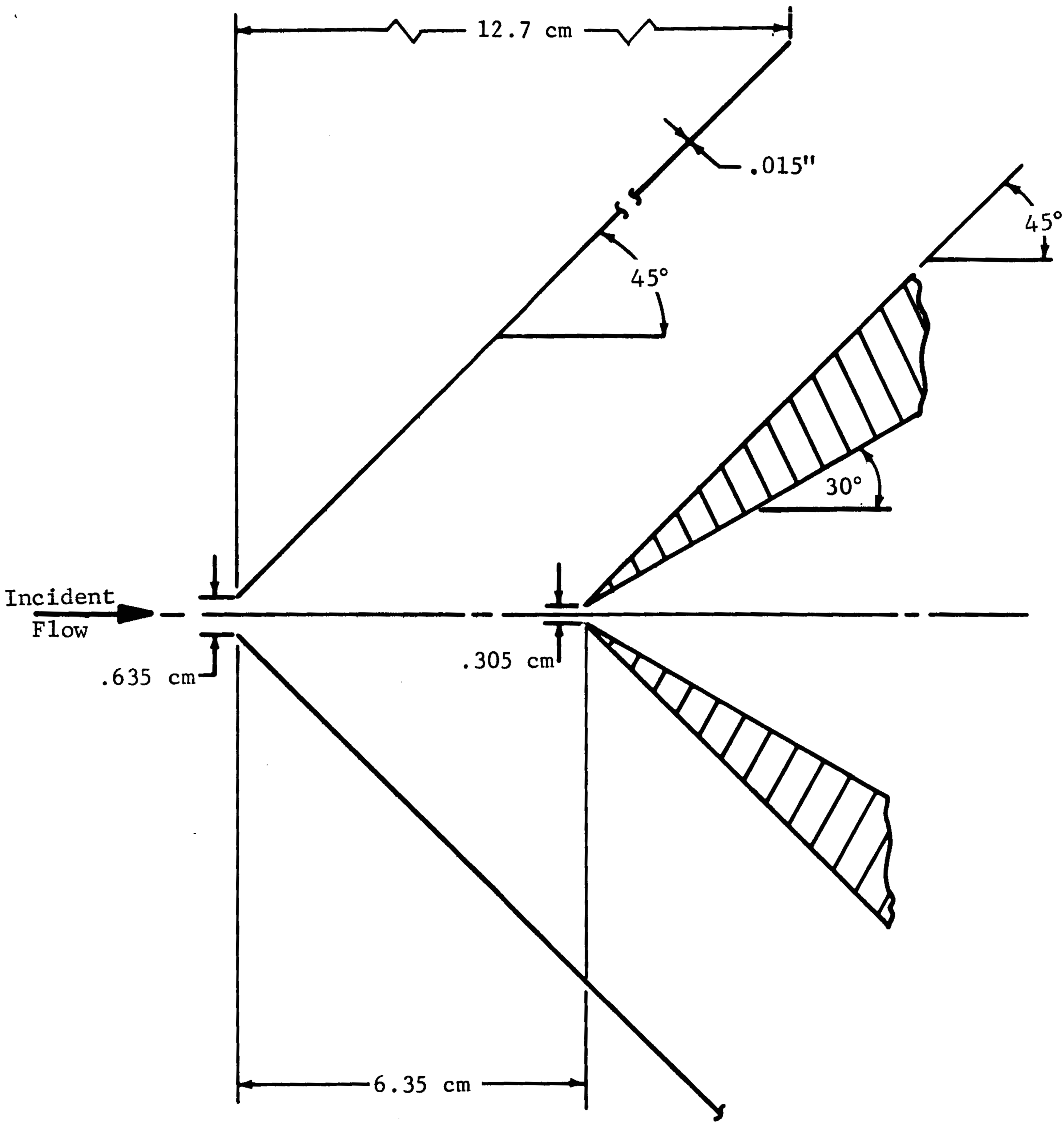
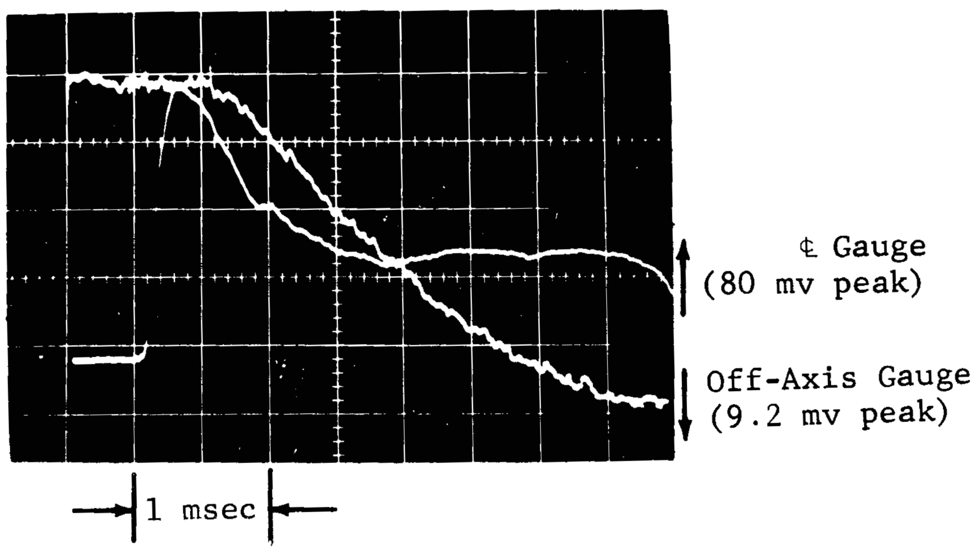


Fig. 6 Sketch of Second Skimmer Assembly Showing Stripper Cone in Typical Position



Notes

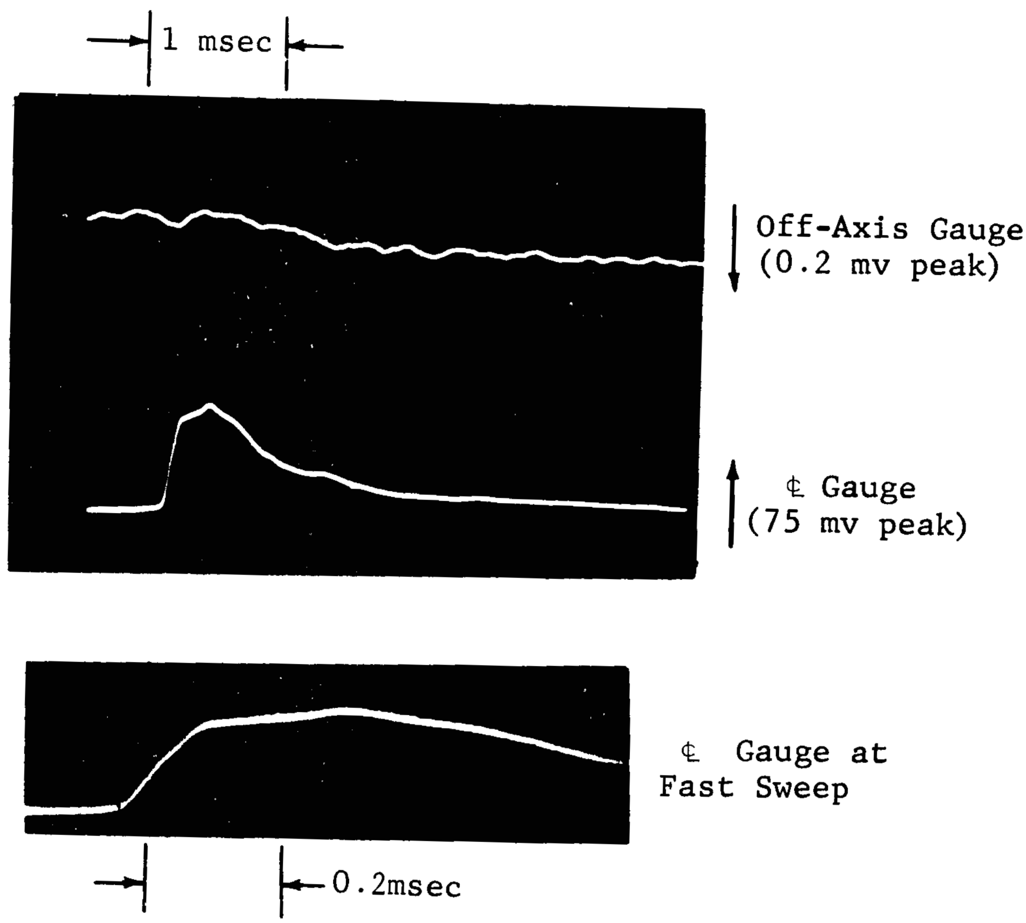
1. Traces start with arrival of shock 0.5 in. upstream of nozzle entrance

2. Nozzle throat diameter = .159 cm
   Nozzle-skimmer distance = 71.120 cm
   Nozzle-detector distance = 121.920 cm
   Skimmer inlet diameter = .305 cm
   $U \approx 2.25 \times 10^5$ cm/sec
   Intensity at skimmer inlet $\approx 10^{20} N_2$ molecules/cm^2-sec

3. Gauge signal is a measure of the instantaneous density of both hot and cold gas

(a) Configuration I, Showing Effect of Cold Gas

Fig. 7 Ionization Gauge Records with Different Configurations



All conditions the same as in Fig. 7a

(b) Configuration II, Showing Reduction of Cold Gas Cloud and Increased Test Duration Resulting from Use of Stripper Cone

Fig. 7 Ionization Gauge Records with Different Configurations

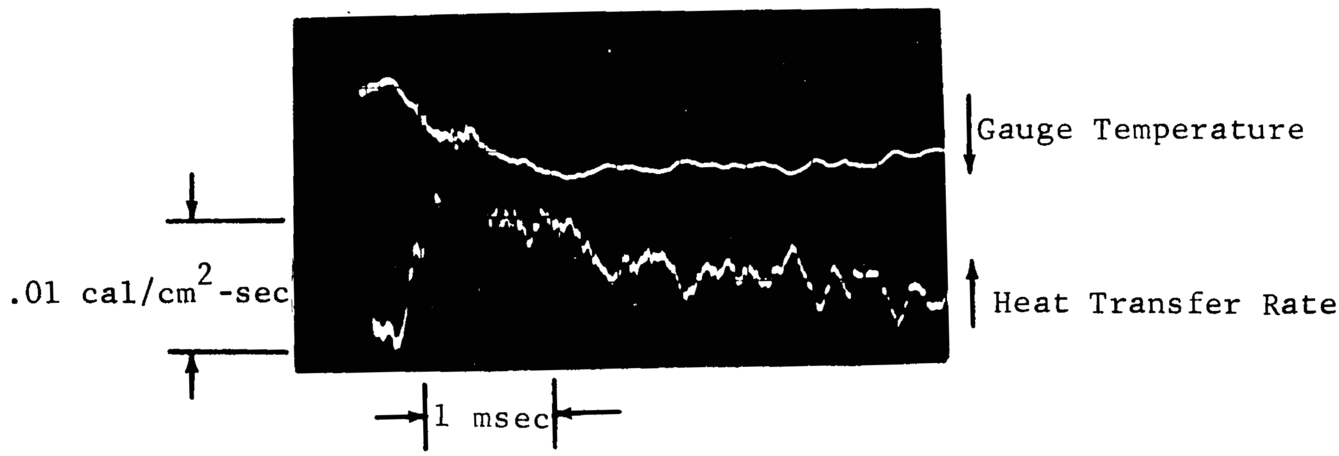
Notes

1. Off-axis gauge signal $<$ 0.1 mv

2. 1st skimmer inlet diameter = .381 cm
   2nd skimmer inlet diameter = .305 cm
   Throat diameter = .063 cm
   Throat - 1st skimmer = 8.573 cm
   1st skimmer - 2nd skimmer = 29.210 cm
   2nd skimmer - detector = 49.530 cm
   $U_{\infty} \approx 1.615 \times 10^{5}$ cm/sec
   Intensity at 2nd skimmer inlet $\approx 6 \times 10^{19} \; \frac{N_2 \text{ molecules}}{\text{cm}^2\text{-sec}}$

(c) Configuration IV

Fig. 7 Ionization Gauge Records with Different Configurations



1) Nozzle throat dia. = .318 cm
1st skimmer inlet diam. = .152 cm
2nd skimmer inlet diam. = .305 cm
Throat - 1st skimmer = 8.573 cm
1st skimmer - 2nd skimmer = 30.480 cm
2nd skimmer - Detector = 17.780 cm

2) $U \approx 2.225 \times 10^5$ cm/sec
Intensity at 2nd skimmer inlet $5 \times 10^{18} \frac{N_2 \text{molecule}}{\text{cm}^2\text{-sec}}$

Fig. 8 Heat Transfer Signals in Test Chamber

Configuration III

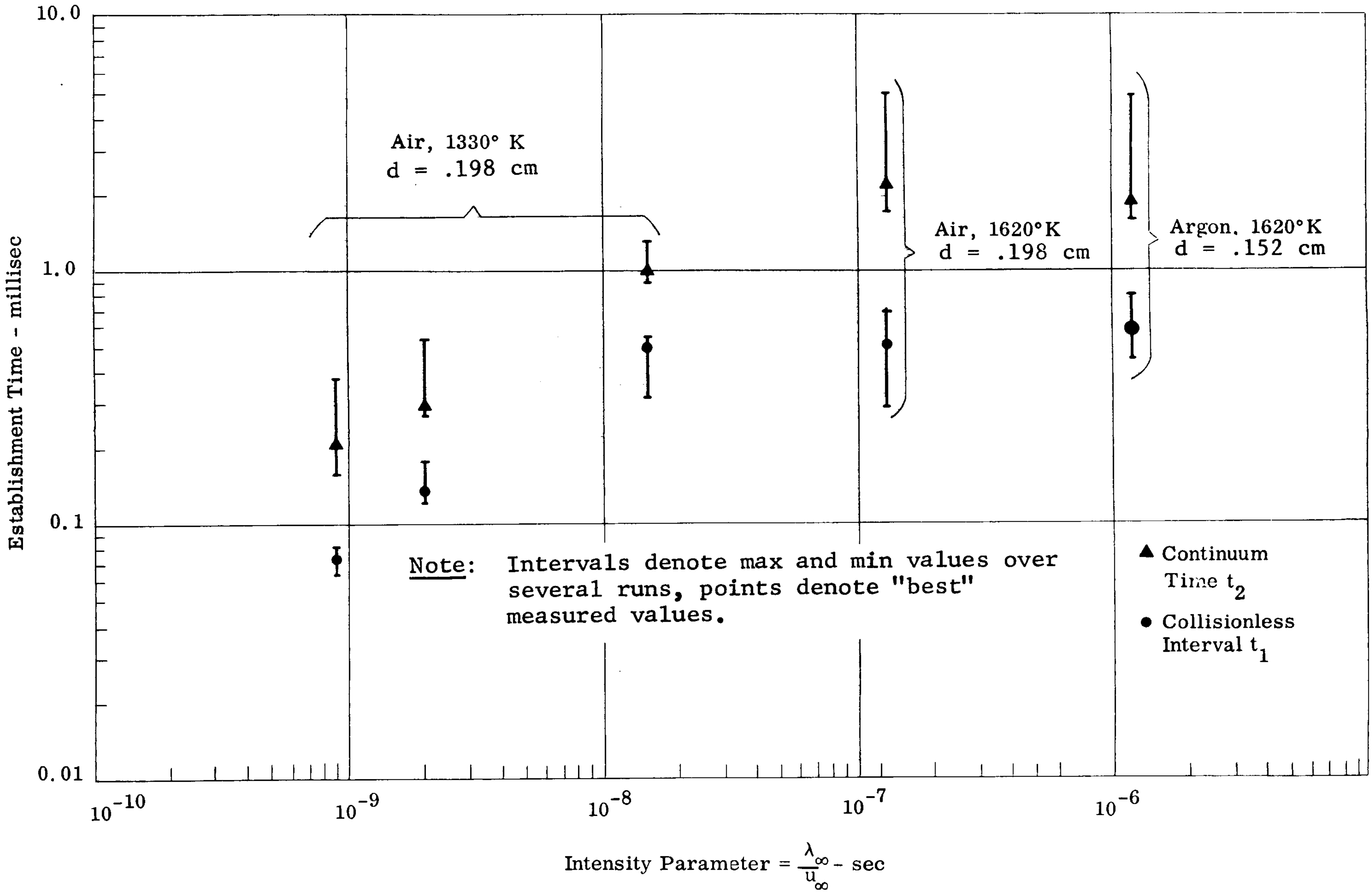


Fig. 9 Continuum and Collisionless Intervals Measured for Skimmer Starting Process

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